1979

The effect of sex, region of the United States, and age of dam on 205 day weaning weights of Hereford cattle

Eldin Alfred Leighton
Iowa State University

8000151

LEIGHTON, ELDIN ALFRED

THE EFFECT OF SEX, REGION OF THE UNITED STATES, AND AGE OF DAM ON 205 DAY WEANING WEIGHTS OF HEREFORD CATTLE.

IOWA STATE UNIVERSITY, PH.D., 1979

University Microfilms International 300 N. ZEEB ROAD, ANN ARBOR, MI 48106

The effect of sex, region of the United States, and age of dam on 205 day weaning weights of Hereford cattle

by

Eldin Alfred Leighton

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Department: Animal Science
Major: Animal Breeding

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1979

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

One of the most economically important traits in beef production has been the weight of calves at weaning. Many producers across the United States market entire calf crops at or near weaning, and the weight of the animals has historically been the measure upon which price was determined. Methods of increasing weaning weights and studies to identify factors influencing weaning weight have been the subject of many research studies in the past. Excellent summaries of most of the published works on factors influencing weaning weights have been made by Petty and Cartwright (1966) and Anderson (1977).

Many studies have clearly shown that genetic influence from both the sire and the dam make important contributions to the weaning weights observed in their offspring. The summary by Petty and Cartwright (1966) reported the estimate of heritability for weaning weight to be .28 after averaging results from more than 50 research studies.

Just as the genotypes inherited by individual animals influence weaning weight, there are many outside environmental factors that work to modify the physical expression of the genotype measured as the observed weaning weight. Before a fair comparison of individual genetic merit for weaning weight can be made, some consideration must be given to minimizing the influence of these environmental effects.

Basically two ways have been used to minimize or eliminate the differences in weaning weight attributable to nongenetic factors before ranking animals on their genetic merit. First has been an attempt to provide management for a group of animals that was as uniform as possible so that under uniform conditions all animals had equal opportunity to express their genetic ability to grow until weaning. Second, for those differences which could not be eliminated by uniform management, statistical adjustments were developed to correct individual weaning weights to a common base before making the genetic ranking.

The purpose of this study was to examine weaning weights of Hereford calves in order to determine the relative importance of sex of the calf, region of the United States in which the calf was raised, and age of dam when the calf was born. Adjustment factors were to be developed for the important effects which could not be controlled by uniform management. The study was undertaken at the request of The American Hereford Association after the Beef Improvement Federation (1975) recommended that each breed association use data collected from their own breed to develop new adjustment factors since the factors then being used had been developed from rather small samples and in some cases from different breeds which may or may not have been representative of the breed to which they were applied. The study also provided an excellent collection of field data on which the properties and computing requirements for some rather recently introduced statistical procedures could be examined.

REVIEW OF LITERATURE

Numerous non-genetic factors are known to influence weaning weights of beef cattle. These include age of the calf at weaning, sex, age of dam when the calf was born, year of birth, season of birth, and preweaning management. The size and direction of the influence of each effect and their interactions has been the subject of many research studies. The reports by Petty and Cartwright (1966) and Anderson (1977) summarized the results from many of these studies. The primary reason for the interest in factors influencing weaning weight has been to either adjust for or eliminate the influence of these nongenetic effects so that a fair ranking of animals based on their genetic ability to attain heavy weights at weaning could be made.

One of the first reports in the literature to develop an adjustment for correction of weaning weight records for beef cattle was by Koger and Knox (1945). They examined the effect of age of the calf at weaning and established the standard, still used by the industry, to adjust weaning weights to a common age of 205 days. This enabled animals of different ages to be managed uniformly including being weaned and weighed on the same day, and then to be compared based on their adjusted 205 day weaning weight for genetic merit of weaning weight. Most studies of weaning weight have reported results for either age corrected records to 205 days (in some cases to the average age of the group) or for average daily gain from birth to weaning. Studies of average daily gain usually included a covariate for age at weaning and sometimes the square of age at weaning as reported by Schaeffer and Wilton (1974a).

The significance of sex of the calf as a factor influencing weaning weight or preweaning average daily gain has been reported by many researchers and summarized by Petty and Cartwright (1966) and Anderson (1977). The advantage, among calves treated alike, has always favored bulls calves with the range in the advantage at weaning being from 5.4 kg to as much as 20.3 kg over the average for heifer calves. Depending on the age at castration, steer calves have usually had an advantage over heifers that was about half the advantage of bull calves. In the recent study by Anderson and Willham (1978), bull calves weighed 20 kg more at weaning than the heifer calves and steers were 13 kg heavier than the heifers.

The importance of age of dam when the calf was born as a factor influencing weaning weights has been well-documented in the literature. The summaries of Petty and Cartwright (1966) and Anderson (1977) covered reports from 29 different sources in the literature for only Angus or Hereford cows. There were also other reports for cows of mixed breeds. In all reports, the calves from the youngest cows were the lightest calves at weaning. As the age of dam increased, the average weight of calves at weaning also increased until the cows were about six years old. There was a general plateau in weaning weight for cows from six to ten years of age and then a steady decline as the cows grew older. The fact of least agreement among reports on the effect of age of dam on weaning weight has been the class boundaries to use in defining the age of dam classes among young cows. Some researchers classified young cows in 12 month intervals while others chose to make the divisions between classes as narrow as two month intervals.

The interaction between sex of calf and age of dam has been reported to be significant in weaning weights by Anderson and Willham (1978) and for preweaning average daily gain by Schaeffer and Wilton (1974a). Reports by Cardellino and Frahm (1971) and Cundiff, et al. (1966a) studying weaning weight records from Oklahoma found the interaction to be nonsignificant.

In all the reports summarized by Petty and Cartwright (1966) and Anderson (1977), the effect for differences in weaning weight over years was always significant. This was to be expected, especially for calves raised under either range or pasture conditions where many weather factors and differing forage management practices could have influenced the quality of forage available. There were no reports in the literature where weaning weights of beef cattle raised under confinement had been reported.

The importance of season of birth on weaning weight has been studied by Marlowe and Gaines (1958), Brown (1960), Marlowe, et al.

(1965), Cundiff, *et al*. (1966a), and Sellers, *et al*. (1970). In each of these reports, the season of birth had a significant effect on weaning weight with calves born during the spring weighing more at weaning than fall-born calves.

The effect of preweaning management, usually studied as the difference between creep and noncreep feeding, has been reported by numerous researchers and summarized by Anderson (1977). Providing supplemental feed for calves prior to weaning increased weaning weight, but the amount of increase was highly dependent on the quality and amount of supplement provided. There were several reports where the increase in weaning weight attributable to supplemental feed was not constant for bulls, steers, and heifers indicating the presence of an interaction between sex of calf and preweaning management. The interaction favored bull calves indicating that bulls achieved greater weight gains than steers or heifers when all had access to a supplemental feed.

MATERIALS AND METHODS

Weaning weight records, adjusted to 205 days of age, from 606,967 registered Hereford calves born between 1958 and 1978 were provided for statistical analysis by the American Hereford Association. All weights were recorded by cattlemen participating in the Total Performance Records program administered by the breed association as a service to the breeders.

The objective of this study was to determine the relative importance of sex of the calf, region of the United States in which the calf was raised, age of dam when the calf was born, and the two-factor interactions among these fixed effects on 205 day adjusted weaning weight (WW) in Hereford cattle. The WW measure was adjusted for the age of the calf at weaning by subtracting birth weight (either actual or 31.6 kg) from the actual weaning weight, computing the average daily gain for the animal, multiplying average daily gain by 205, and then adding the birth weight as recommended by the Beef Improvement Federation (1976). Additional statistical adjustments for the effects of herd within region, contemporary groups within herd, and cows within herd were also included in the model subsequently referred to as the mixed model.

Only calves whose age at weaning was between 160 and 240 days were included in the study. This restriction eliminated 145,396 records which were older than 240 days. There were no records with age at weaning younger than 160 days.

In developing the criteria to define contemporary groups within herd for the mixed model, consideration was given to the results reported by Anderson and Willham (1978) in which the effect of differences in management (creep versus non-creep feeding) on WW was reported to be a highly significant ($P < .005$) source of variation in WW. As they pointed out, however, the wide range in types and levels of supplemental feeding made it impossible to recommend a standard set of adjustment factors for the management effect on WW. Hence, in the present study, the effect of management, through either creep or non-creep feeding, was incorporated into the definition of contemporary groups of animals within herd. Strictly, the contemporary group was defined to be all animals within a particular herd which were managed alike with regard to supplemental feeding, were weighed and weaned on exactly the same day, and were within the 160 through 240 day range in age at weaning. Only groups with 10 or more animals and fewer than 10 percent steer records were kept for analysis, however, all steer records were eliminated from the study. These restrictions for defining contemporary groups within herd caused another 79,496 records to be rejected leaving a total of 382,075 weaning weight records from 1,153 herds for study.

To examine the importance of the region of the United States on WW, it was necessary to divide the United States into distinct geographic areas. Nine separate areas of the United States were defined by taking into consideration average levels of rainfall and temperature, forage production, management practices, and characteristics of terrain to define the regions shown in Figure 1. Classifying the region of origin for each record was possible by using the United States Postal Service Zip Code (1977) associated with the address for each herdowner. Within the Zip Code structure, the first digit defined a broad region of the United States. The second and third digits defined regional distribution centers within the major regions. All areas served by the regional distribution centers were numbered in the fourth and fifth digits of the Zip Code. Careful study of the United States allowed defining the nine geographic regions by drawing region boundaries around areas served by regional distribution centers. Thus, the first three digits in the Zip Code uniquely defined the geographic regions free from any state line boundary restrictions. The nine regions were labeled for all discussion in this study as Northeast, Cornbelt, South, Gulf Coast, Upper Plains, Lower Plains, Rocky Mountains, Desert Southwest, and Pacific.

A classification of age of dam when the calf was born, which was recorded in months and included cows in the range from 20 through 240 months, was necessary to examine the effect of age of dam on WW. The recommendations of the Beef Improvement Federation (1976) for classifying age of dam were not used in the present study because the range over which cows were classified in groups one and two were felt to be to wide. Their recommendations placed cows from 21 through 33 months of age in class one while cows from

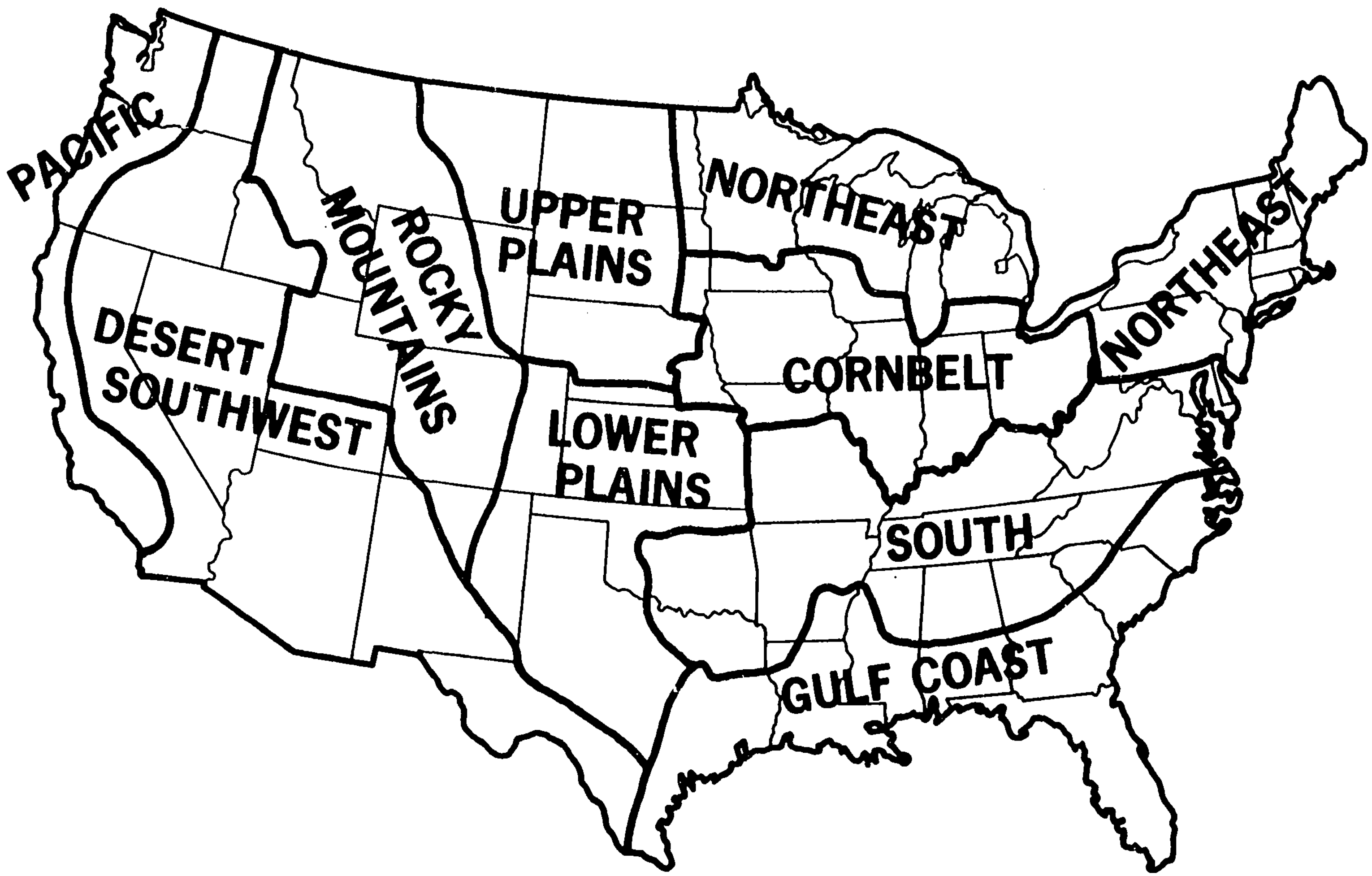

Figure 1. Boundary definitions for nine geographic regions of the United States

34 though 46 months were placed in class two. The nine age of dam classes used in this study are defined in Table 1. Young cows were classified in eight month intervals from 20 through 27 months in class one and 28 through 35 months in class two while class three included cows whose age was from 36 to 48 months. The shorter range in age used to define classes one and two was an attempt to separate cows calving for the first time at two years of age from those cows which calved for the first time at two and one-half years of age. Any cows calving for the first time on or after 25 months of age would not have had their second record in class two but rather would have skipped to class three.

Season of birth was demonstrated by several researchers (Marlowe and Gaines (1958), Brown (1960), Marlowe, et al. (1965), Cundiff, et al. (1966a), and Sellers, et al. (1970)) as a significant factor influencing WW. The effect was not included in the present study because within herds usually only one season of birth would have been found. For those herds where calving was practiced year round or where both spring and fall calving was practiced, the effect for contemporary groups within herd defined over an 80 day range would have accounted for the differences reported in the literature as attributable to season of birth.

Statistical Methodology

The general linear model, represented by

$$y = X\beta + e \qquad (1)$$

Table 1. Definition of age of dam classes

Class	Age range (months)
1	20 - 27
2	28 - 35
3	36 - 47
4	48 - 59
5	60 - 71
6	72 - 95
7	96 - 119
8	120 - 143
9	144 - 240

has been thoroughly reviewed and discussed by Searle (1971). Basic assumptions are

$$\text{var} \begin{bmatrix} y \\ e \end{bmatrix} = \begin{bmatrix} I & \phi \\ \phi & I \end{bmatrix} \sigma_e^{\,2} \tag{2}$$

and

$$E \begin{bmatrix} y \\ e \end{bmatrix} = \begin{bmatrix} X\beta \\ \phi \end{bmatrix} \tag{3}$$

with β assumed to represent only fixed effects and where I = the identity matrix, ϕ = the null matrix, and X is the matrix of zeroes and ones which relates the elements of β to the elements of y. The normal equations for determining ordinary least-squares (OLS) solutions for β are then

$$X'X\beta = X'y \tag{4}$$

and for $X'X$ of full rank, the unique solution vector is

$$\hat{\beta} = (X'X)^{-1}\, X'y \tag{5}$$

Also

$$\begin{aligned} \text{var }(\hat{\beta}) &= \text{var } [(X'X)^{-1}\, X'y] \\ &= (X'X)^{-1}\, X' \text{ var }(y)\; X(X'X)^{-1} \\ &= (X'X)^{-1}\, \sigma_e^2 \end{aligned} \tag{6}$$

Aitken (1934) showed that the assumption in (2) could be generalized by defining the variance, covariance matrix among the elements of y as

$$\text{var } [y] = \begin{bmatrix} \sigma^2_{11} & \sigma_{12} & \cdots & \sigma_{1n} \\ & \sigma^2_{22} & \cdot & \cdot \\ & & \ddots & \vdots \\ & & & \sigma^2_{nn} \end{bmatrix}$$

$$\text{var } [y] = U \tag{7}$$

Then, the least-squares equations to obtain best linear unbiased estimates (BLUE) of β in (1) are written as

$$(X'U^{-1}X)\beta = X'U^{-1}y \tag{8}$$

The generalized least-squares (GLS) estimates of β are then

$$\hat{\beta} = (X'U^{-1}X)^{-1} X'U^{-1}y \tag{9}$$

and
$$\mathrm{var}\ (\hat{\beta}) = (X'U^{-1}X)^{-1} \tag{10}$$

To make tests of significance concerning classes of effects contained in the vector β, Harvey (1960) has shown that the partial sum of squares for the t^{th} effect can be obtained using the formula

$$SS_t = \hat{\beta}_t' \left[(X'U^{-1}X)^{-1}_{tt}\right]^{-1}\hat{\beta}_t \tag{11}$$

where tt denotes the segment of the inverse matrix for that effect. Equation (11) reduces to

$$SS_t = \hat{\beta}_t' \left[(X'X)^{-1}_{tt}\right]^{-1}\hat{\beta}_t \tag{12}$$

if $U = I\ \sigma_e^2$.

The fixed model examined by OLS was defined as

$$y_{ijkl} = \mu + s_i + r_j + a_k + (sr)_{ij} + (sa)_{ik} + (ra)_{jk} + e_{ijkl} \tag{13}$$

where y_{ijkl} = the observed WW of the l^{th} animal in the i^{th} sex class, j^{th} region within the United States, and k^{th} age of dam class,

μ = the overall mean,

s_i = the effect of the i^{th} sex, i = 1,2,

r_j = the effect of the j^{th} region within the United States, j = 1, ..., 9,

a_k = the effect of the k^{th} age of dam class, k = 1, ..., 9,

$(sr)_{ij}$ = the effect of interaction between the i^{th} sex class and the j^{th} region,

$(sa)_{ik}$ = the effect of interaction between the i^{th} sex class and the k^{th} age of dam class,

$(ra)_{jk}$ = the effect of interaction between the j^{th} region and the k^{th} age of dam class,

and e_{ijkl} = random error.

The computing strategy used to obtain the vector of least-squares constants for the model described by (13) was essentially what Yates (1934) called a weighted squares of means analysis. The process involved, first, computing the sex, region, age of dam subclass means and the total sum of squares, and then, second, completing an analysis of these subclass means. The model in (13) was represented by the general linear model in (1) and the solution vector defined by (5) was the objective. The observations were represented by the model.

$$Y = T\delta + e \tag{14}$$

with

$$\hat{\delta} = (T'T)^{-1}T'Y \tag{15}$$

where $\hat{\delta}$ was the vector of subclass means and

$$\begin{aligned} \text{var } (\hat{\delta}) &= (T'T)^{-1}\sigma_e^2 \\ &= U \end{aligned} \tag{16}$$

Completing the analysis of subclass means was then possible using (8) and defining a transformation matrix K such that

$$TK = X \tag{17}$$

to produce the equations

$$(K'U^{-1}K)\beta = K'U^{-1}\hat{\delta}$$

$$K'(T'T)\frac{1}{\sigma_e^2}K\beta = K'(T'T)\frac{1}{\sigma_e^2}(T'T)^{-1}T'Y$$

$$(K'T'TK)\beta = K'T'Y \tag{18}$$

Substituting (17) in (18), does, in fact, produce the equations defined in (4) and solution given by (5). This strategy was computationally much easier because obtaining the subclass means, $\hat{\delta}$, was relatively simple even for the large number of observations. Choosing the appropriate matrix K then involved only a matrix of order equal to the number of subclasses by the number of degrees of freedom in the model in (13). Should one wish to examine a variation of the model in (13), only a new matrix K must be defined making it unnecessary to reexamine the entire data set. Least-squares means and standard errors of least-squares means were then computed for each main effect class and each interaction subclass using the procedures outlined by Harvey (1960). Additionally, the effective number of observations that would have occurred in each class had the data been perfectly balanced was computed as the reciprocal of the linear function of inverse elements, from solution of (18), used to compute the standard errors of each least-squares mean. The theoretical considerations used in obtaining the effective number of observations per class or subclass have been discussed by Thompson (1976). Computed in this way, the effective number of observations per subclass reflected the penalty that was paid by adjusting for disproportionate subclass frequencies.

Henderson (1973) gave a thorough review of his development of the mixed model equations as a partition of the general linear model in (1). Define the partitioning of (1) as

$$Y = X\beta + e$$

$$Y = \begin{bmatrix} W & Z \end{bmatrix} \begin{bmatrix} b \\ u \end{bmatrix} + e$$

$$Y = Wb + Zu + e \tag{19}$$

where W and Z are n x p and n x q design matrices, b is a vector of fixed effects, u is a vector of random effects, and e is the vector of random errors. Also define

$$\text{var} \begin{bmatrix} u \\ e \end{bmatrix} = \begin{bmatrix} G & \phi \\ \phi & R \end{bmatrix} \tag{20}$$

which are assumed to be known. It is then possible to find the var (Y) in (19) as

$$\text{var}\ (Y) = ZGZ' + R = V \tag{21}$$

Henderson (1963) demonstrated that the inverse of the matrix V in (21) was

$$V^{-1} = R^{-1} - R^{-1}Z(Z'R^{-1}Z + G^{-1})^{-1}\ Z'R^{-1} \tag{22}$$

and that by equating V^{-1} in (22) to U^{-1} in (8), the mixed model equations are written as

$$W'R^{-1}Wb + W'R^{-1}Z\ u = W'R^{-1}Y$$

$$Z'R^{-1}Wb + (Z'R^{-1}Z + G^{-1})\ u = Z'R^{-1}Y \tag{23}$$

Now, if $R = I\sigma_e^2$ and $G = I\sigma_u^2$, the equations in (23) reduce further to

$$W'Wb + W'Z\ u = W'Y$$

$$Z'Wb + (Z'Z + I\frac{\sigma_e^2}{\sigma_u^2})\ u = Z'Y \tag{24}$$

As Henderson (1963) pointed out, these equations, assuming that u is a vector of random variables, are identical to the normal equations one would obtain by assuming all effects to be fixed except for the addition of $I \frac{\sigma_e^2}{\sigma_u^2}$ to the random effect portion of the coefficient matrix.

Henderson (1973) gave the desirable properties of the equations in (24.). The estimates obtained for the fixed effects are BLUE, and the estimates obtained for the random effects are best linear unbiased predictors (BLUP). Further, by assuming normality for the distributions of both u and e, the equations are the maximum likelihood equations which maximize the likelihood function for the set of data under consideration.

The specific model used in the study was

$$y_{ijklmn} = \mu + s_i + r_j + a_k + (sr)_{ij} + (sa)_{ik} + (ra)_{jk} + h_{jl} + g_{jlm} + c_{jln} + e_{ijklmn} \qquad (25)$$

where y_{ijklmn} = the observed WW of the calf from the n^{th} cow and m^{th} contemporary group in the l^{th} herd of the j^{th} region and in the k^{th} age of dam class and i^{th} sex class,

μ, s_i, r_j, a_k, $(sr)_{ij}$, $(sa)_{ik}$, $(ra)_{ik}$ are as defined in (13),

h_{jl} = the random effect of the l^{th} herd within the j^{th} region,

g_{jlm} = the random effect of the m^{th} contemporary group within the l^{th} herd and j^{th} region,

c_{jln} = the random effect of the n^{th} cow within the l^{th} herd and j^{th} region,

and e_{ijklmn} = random error.

The model in (25) can be written as

$$\begin{aligned} Y &= Wb + Zu + e \\ &= Wb + Hh + Dg + Cd + e \end{aligned} \tag{26}$$

where $Z = [H\ D\ C]$ and $u' = [h'\ g'\ d']$ with H, D, and C representing the partitions of the design matrix Z such that H refers to herds, D refers to contemporary groups within herd, and C refers to cows. To develop the normal equations for the model in (26), define

$$\text{var}\ (u) = \text{var}\begin{bmatrix} h \\ g \\ d \end{bmatrix} = \begin{bmatrix} I\sigma_h^2 & \phi & \phi \\ \phi & I\sigma_g^2 & \phi \\ \phi & \phi & I\sigma_d^2 \end{bmatrix} \tag{27}$$

Substituting the partition of Z and the var (u) in (24), the mixed model equations for the model in (26) were

$$\begin{bmatrix} W'W & W'H & W'D & W'C \\ H'W & H'H + I\frac{\sigma_e^2}{\sigma_h^2} & H'D & H'C \\ D'W & D'H & D'D + I\frac{\sigma_e^2}{\sigma_g^2} & D'C \\ C'W & C'H & C'D & C'C + I\frac{\sigma_e^2}{\sigma_d^2} \end{bmatrix} \begin{bmatrix} b \\ h \\ g \\ d \end{bmatrix} = \begin{bmatrix} W'Y \\ H'Y \\ D'Y \\ C'Y \end{bmatrix} \tag{28}$$

Because prior estimates of the variance components for herds, contemporary groups within herd, cows within herd, and error were not available for this data, a Henderson (1953) Method I analysis was used to obtain estimates of the variance components. The model was

$$y_{ijk} = \mu + h_i + g_{ij} + c_{ik} + e_{ijk} \tag{29}$$

where y_{ijk} = the observed WW of the calf from the k^{th} cow and the j^{th} contemporary group in the i^{th} herd,

μ = the overall mean,

h_i = the effect of the i^{th} herd, $i = 1, \ldots, r$,

g_{ij} = the effect of the j^{th} contemporary group within the i^{th} herd, $j = 1, \ldots, s_i$,

c_{ik} = the effect of the k^{th} cow within the i^{th} herd, $k = 1, \ldots, t_i$,

and e_{ijk} = random error.

A Method I analysis for variance component estimation is accomplished by computing a sum of squares, equating the sum of squares to its expected value, and solving the system of equations for the components. In this case, the total sum of squares, the correction factor for the mean, and uncorrected sums of squares for herds, contemporary groups within herd, and cows within herd were all equated to their expected values and the system solved simultaneously. The equations were

$$\begin{bmatrix} N & \frac{1}{N}K_1 & \frac{1}{N}K_2 & \frac{1}{N}K_3 & 1 \\ N & N & K_4 & K_5 & r \\ N & N & N & K_6 & K_6 \\ N & N & K_7 & N & K_7 \\ N & N & N & N & N \end{bmatrix} \begin{bmatrix} \mu^2 \\ \sigma_h^2 \\ \sigma_g^2 \\ \sigma_d^2 \\ \sigma_e^2 \end{bmatrix} = \begin{bmatrix} CF \\ HSS \\ GSS \\ CSS \\ TSS \end{bmatrix} \tag{30}$$

where $K_1 = \sum_i n_{i\cdot\cdot}^2$,

$K_2 = \sum_{ij} n_{ij\cdot}^2$,

$K_3 = \sum_{ik} n_{i\cdot k}^2$,

$$K_4 = \sum_i \left[\frac{\sum_j n_{ij\cdot}^2}{n_{i\cdot\cdot}}\right],$$

$$K_5 = \sum_i \left[\frac{\sum_k n_{i\cdot k}^2}{n_{i\cdot\cdot}}\right],$$

$K_6 = \sum_i s_i$ = total number of contemporary groups,

$K_7 = \sum_i t_i$ = total number of cows,

$N = \sum_{ijk} n_{ijk}$ = total number of observations,

$CF = N\bar{y}^2 = \frac{1}{N}\left[\sum_{ijk} y_{ijk}\right]^2$ = correction factor,

$HSS = \sum_i \left[\frac{1}{n_{i\cdot\cdot}}\left(\sum_{jk} y_{ijk}\right)^2\right]$ = uncorrected herd sum of squares,

$GSS = \sum_{ij} \left[\frac{1}{n_{ij\cdot}}\left(\sum_k y_{ijk}\right)^2\right]$ = uncorrected group sum of squares,

$CSS = \sum_{ik} \left[\frac{1}{n_{i\cdot k}}\left(\sum_j y_{ijk}\right)^2\right]$ = uncorrected cow sum of squares,

and $TSS = \sum_{ijk} y_{ijk}^2$ = total sum of squares.

Since the equations in (30) were of the form $Ax = B$, solution for x, the vector of variance components, was found by $x = A^{-1} B$.

Due to the large number of random effect equations (188,236), the computing strategy used to obtain the mixed model estimates for the vector b in (28) involved systematically absorbing the random equations into the fixed equations as each herd was processed. The tedious algebra of this absorption process was well described by Anderson (1977) for a similar mixed model. First, the absorption process required the data to be in order by herds and cows within herd. As individual observations were processed, appropriate values were accumulated for the fixed equations, the herd equation, equations for each contemporary group within herd, and the cow equation. As soon as all records for a particular cow were accumulated, that cow equation was absorbed into the herd equation, into the equations for contemporary groups within herd, and into the fixed equations. After the absorption of a single cow equation, the appropriate cow equation storage areas were cleared, and processing continued for the next cow in the herd. When all cows in the herd had been processed, the herd equation was absorbed into the equations for contemporary groups within herd and into the fixed equations. Finally, only the contemporary group equations for this herd remained along with the fixed effect equations. The contemporary group equations were absorbed into the fixed equations, and processing for a particular herd was finished. The storage areas for all the random equations were then cleared, and each successive herd was processed until all the data had been entered. Each time an absorption operation was completed, appropriate accumulations were made to compute the sum of squares and the degrees of freedom accounted for by the three sets of random effects. The fixed equations remaining after the absorption of all random effect equations were then solved using the same procedure outlined for the OLS model in (18).

To provide continuity in notation, the algebra of the absorption process is given here. First, the equations given in (28) were rewritten as

$$W'Wb + W'Hh + W'Dg + W'Cd = W'y \tag{31}$$

$$H'Wb + (H'H + I\frac{\sigma_e^2}{\sigma_h^2})h + H'Dg + H'Cd = H'y \tag{32}$$

$$D'Wb + D'Hh + (D'D + I\frac{\sigma_e^2}{\sigma_g^2})g + D'Cd = D'y \tag{33}$$

$$C'Wb + C'Hh + C'Dg + (C'C + I\frac{\sigma_e^2}{\sigma_d^2})d = C'y \tag{34}$$

Now, equation (34) was solved for d in terms of b, h, and g as

$$d = (C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} (C'y - C'Wb - C'Hh - C'Dg)$$

$$= (C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'y - (C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} (C'Wb + C'Hh + C'Dg) \tag{35}$$

Then (35) was substituted in (31), (32), and (33) to give the equations

$$W_1'W_1b + W_1'H_1h + W_1'D_1g = W_1'y \tag{36}$$

$$H_1'W_1b + (H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})h + H_1'D_1g = H_1'y \tag{37}$$

and

$$D_1'W_1b + D_1'H_1h + (D_1'D_1 + I\frac{\sigma_e^2}{\sigma_g^2})g = D_1'y \tag{38}$$

where

$$W_1'W_1 = W'W - W'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'W,$$

$$W_1'H_1 = W'H - W'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'H = (H_1'W_1)',$$

$$W_1'D_1 = W'D - W'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'D = (D_1'W_1)',$$

$$H_1'H_1 = H'H - H'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'H,$$

$$H_1'D_1 = H'D - H'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'D = (D_1'H_1)',$$

$$D_1'D_1 = D'D - D'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'D,$$

$$W_1'Y_1 = W'Y - W'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'Y,$$

$$H_1'Y_1 = H'Y - H'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'Y,$$

and

$$D_1'Y_1 = D'Y - D'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'Y.$$

Second, to absorb the herd equations, (37) was solved for h in terms of b and g as

$$h = (H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} (H_1'Y - H_1'W_1b - H_1'D_1g)$$

$$= (H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'Y_1 - (H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} (H_1'W_1b + H_1'D_1g) \tag{39}$$

Equation (39) was then substituted in equations (36) and (38) to produce

$$W_2'W_2b + W_2'D_2g = W_2'Y_2 \tag{40}$$

and

$$D_2'W_2b + (D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})g = D_2'Y_2 \tag{41}$$

where

$$W_2'W_2 = W_1'W_1 - W_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'W_1,$$

$$W_2'D_2 = W_1'D_1 - W_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'D_1 = (D_2'W_2)',$$

$$D_2'D_2 = D_1'D_1 - D_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'D_1$$

$$W_2'Y_2 = W_1'Y_1 - W_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'Y_1,$$

and

$$D_2'Y_2 = D_1'Y_1 - D_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'Y_1.$$

Finally, all that remained to complete the absorption process was to solve (41) for g in terms of b and make the substitution in (40). The reduced set of fixed equations, after absorbing all the random effects, was then

$$W_3'W_3b = W_3'Y_3 \tag{42}$$

where

$$W_3'W_3 = W_2'W_2 - W_2'D_2(D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})^{-1} D_2'W_2,$$

and

$$W_3'Y_3 = W_2'Y_2 - W_2'D_2(D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})^{-1} D_2'Y_2.$$

To complete the analysis of variance and to obtain estimates of the standard errors of the fixed effect least-squares means, the sum of squares explained by all the random effects, the sum of squares explained by the fixed effects after adjusting for the random effects, and the total sum of squares were required. One method of obtaining the sum of squares for random effects was outlined by Schaeffer.[1] His technique required that the appropriate sequential sums of squares be accumulated as the absorption of all the random equations was being completed for cows within herd, herds within region after adjusting for cows within herd and then contemporary groups within herd after adjusting for both cows within herd and herd within region. The process was begun by accumulating the total sum of squares as each new record was processed as

$$TSS = \sum_{ijklmn} Y_{ijklmn}^2 = Y'Y,$$

and $$N = \sum_{ijklmn} n_{ijklmn}$$

= the total number of observations in the data set.

The cow sum of squares was computed as

$$CSS = Y'C(C'C + I\frac{\sigma_e^2}{\sigma_d^2})^{-1} C'Y$$

where $C'Y$ was the right hand side for the cow equations and

---

[1]Schaeffer, L. R. Department of Animal Science, University of Guelph, Guelph, Ontario, Canada. Personal communication.

$(C'C + I\frac{\sigma_e^2}{\sigma_d^2})$ was the diagonal sub-matrix of coefficients for the cow equations with the diagonal elements simply counting the number of calves per cow. Since $C'C$ was diagonal, the cow sum of squares was accumulated with the absorption of each cow equation.

The herd sum of squares, after absorbing the cow equations, was computed in the same fashion as the cow sum of squares as

$$HSS = Y_1'H_1(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})^{-1} H_1'Y_1$$

where $H_1'Y_1$ was the vector of right hand sides for the herd equations after absorbing the cow equations and $(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})$ was the diagonal sub-matrix of coefficients for the herd equations after absorbing the cow equations. Again, $(H_1'H_1 + I\frac{\sigma_e^2}{\sigma_h^2})$ was diagonal so that its inverse was computed one equation at a time, and the HSS was accumulated as each herd equation was absorbed.

Finally, the group sum of squares, after absorbing equations for both cows within herd and herds, was computed as

$$GSS = Y_2'D_2(D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})^{-1} D_2'Y_2$$

where $D_2'Y_2$ was the vector of right hand sides for the contemporary groups within herd equations, and $(D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})$ was the block diagonal sub-matrix of coefficients for the contemporary group equations after absorbing both the cows within herd and the herd equations. Because $(D_2'D_2 + I\frac{\sigma_e^2}{\sigma_g^2})$ was a block diagonal matrix, the inverse could be computed as the matrix of inverses for each block, and the GSS was then accumulated one group at a time.

When all the random equations had been absorbed to produce the set of equations in (42), solution for b in (42) was found as

$$\hat{b} = (W_3'W_3)^{-1} W_3'Y$$

after imposing the restriction on b that $\mu = 0$. The sum of squares explained by the fixed effects in the model, after absorbing all the random effects was then computed as

$$FSS = \hat{b}' W_3'Y.$$

An estimate of σ_e^2 was then available as

$$\hat{\sigma}_e^2 = (TSS - CSS - HSS - GSS - FSS) /N - p - q$$

where N was the total number of observations, p was the rank of $W_3'W_3$ or the number of independent fixed equations in the model, and q was the number of independent random equations. It was not known whether the number of random equations should have been subtracted from the denominator in arriving at the estimate for σ_e^2.

RESULTS

The Henderson (1953) Method I analysis used to obtain variance component estimates for herds, contemporary groups within herd, cows within herd, and error was completed by solving the set of simultaneous equations in the form $Ax = B$ where

$$A = \begin{bmatrix} 382{,}075 & 1{,}443 & 66 & 3 & 1 \\ 382{,}075 & 382{,}075 & 40{,}356 & 2{,}438 & 1{,}153 \\ 382{,}075 & 382{,}075 & 382{,}075 & 11{,}054 & 11{,}054 \\ 382{,}075 & 382{,}075 & 176{,}029 & 382{,}075 & 176{,}029 \\ 382{,}075 & 382{,}075 & 382{,}075 & 382{,}075 & 382{,}075 \end{bmatrix},$$

$$x' = \begin{bmatrix} \mu^{2\,1} & \sigma^2_h & \sigma^2_g & \sigma^2_d & \sigma^2_e \end{bmatrix},$$

and

$$B = \begin{bmatrix} 5{,}367{,}508 \\ 100{,}637{,}409 \\ 208{,}668{,}204 \\ 294{,}745{,}528 \\ 433{,}545{,}783 \end{bmatrix}.$$

The estimates produced were $\hat{\sigma}^2_h = 216.0$, $\hat{\sigma}^2_g = 299.5$, $\sigma^2_d = 231.9$, and $\hat{\sigma}^2_e = 374.2$. The ratios, used to augment the random equations in the mixed model, were $\hat{\sigma}^2_e/\hat{\sigma}^2_h = 1.73$, $\hat{\sigma}^2_e/\sigma^2_g = 1.25$, $\hat{\sigma}^2_e/\hat{\sigma}^2_d = 1.61$.

The analyses of variance for both the fixed and the mixed models are presented in Tables 2 and 3 respectively. The fixed

---

[1]Actually estimated μ^2 - 200 kg because each observation was coded by subtracting 200.

Table 2. Analysis of variance for the fixed model

Source	Degrees freedom	Mean square	F value	Coefficients for expected mean square σ^2_e	α^2_{RA}	α^2_{SA}	α^2_{SR}	α^2_A	α^2_R	α^2_S
Sex (S)	1	12,734,210	13,366.2***	1.0						57,222
Region (R)	8	244,891	257.0***	1.0					28,709	
Age of dam (A)	8	706,927	742.0***	1.0				13,622		
S x R	8	37,244	39.1***	1.0			39,235			
S x A	8	28,393	29.8***	1.0		41,268				
R x A	64	11,875	12.5***	1.0	5,926					
Residual	381,977	953		1.0						

***$p < 0.005$.

Table 3. Analysis of variance for the mixed model

Source	Degrees freedom	Mean square	F value	Coefficients for expected mean square σ^2_e	α^2_{RA}	α^2_{SA}	α^2_{SR}	α^2_{A}	α^2_{R}	α^2_{S}
Random effects	188,236	1,483	2.3***							
Sex (S)	1	6,615,428	10,421.9***	1.0						36,188
Region (R)	8	998	1.6	1.0					149	
Age of dam (A)	8	324,027	510.5***	1.0				8,878		
S x R	8	12,815	20.2***	1.0			24,101			
S x A	8	18,208	28.7***	1.0		30,145				
R x A	64	1,772	2.8***	1.0	3,982					
Residual	193,741	635		1.0						

***$p < 0.005$.

model accounted for 15.6 percent of the total variation observed in WW while the mixed model accounted for 71.6 percent of the variation. The substantial increase in the amount of variation in WW explained by the mixed model over the fixed model was the result of including the random effects for herds, contemporary groups within herd, and cows within herd in the model. These three sets of random effects were alone accounting for 56 percent of the observed variation in WW. Reductions in sums of squares for both models are given in Table 4.

All the main effects (sex of the calf, region of the United States, and age of dam) and the two-factor interactions among the main effects were highly significant ($P < .005$) sources of variation in WW in the fixed model. In the mixed model analysis, the main effects for sex of the calf and age of dam along with the two factor interactions were also highly significant ($P < .005$) sources of variation in WW. Region of the United States, as a main effect in the mixed model analysis, was a nonsignificant ($P > .20$) source of variation, however.

Least-squares means for each of the main effect classes in both the fixed and mixed models are given in Table 5. Subclass least-squares means are presented in Tables 6, 7, and 8 for the interactions between sex of the calf and region of the United States, sex of the calf and age of dam, and region of the United States and age of dam, respectively.

Table 4. Sums of squares, reductions in sums of squares, and degrees of freedom used to complete the WW analysis for both the fixed and mixed models

Source	Degrees freedom	Fixed model	Mixed model
Total sum squares	382,075	433,545,783	433,545,783
R (fixed effects)	98	69,628,977	31,383,379
R (random effects)	188,236		279,183,496
Residual sum squares			
Fixed model	381,977	363,916,806	
Mixed model	193,741		122,978,909

Table 5. Least-squares means and standard errors for main effects in both the fixed and mixed models

Effect	Number observed	Fixed model Effective number	Fixed model LS mean (kg)	Fixed model Std. error	Mixed model Effective number	Mixed model LS mean (kg)	Mixed model Std. error
Overall mean	382,075	90,490	195	0.10	791	193	0.90
Bull calves	191,291	49,615	205	0.14	781	203	0.90
Heifer calves	190,784	51,486	184	0.14	783	184	0.90
Northeast	14,650	11,381	198	0.29	56	194	3.36
Cornbelt	25,641	19,574	198	0.22	143	196	2.11
South	27,965	20,648	194	0.22	128	194	2.22
Gulf Coast	12,660	8,480	182	0.34	45	185	3.77
Upper Plains	97,036	68,041	195	0.12	291	195	1.48
Lower Plains	86,272	57,848	194	0.13	299	191	1.46
Rocky Mts.	64,476	48,576	195	0.14	212	196	1.73
Desert S.W.	50,572	39,980	197	0.15	201	194	1.78
Pacific Coast	2,803	1,953	198	0.70	32	194	4.45
Age of dam 1	29,054	5,884	178	0.40	641	178	1.00
Age of dam 2	29,674	10,504	185	0.30	703	184	0.95
Age of dam 3	61,628	19,151	191	0.22	755	191	0.92
Age of dam 4	56,407	18,774	197	0.23	755	197	0.92
Age of dam 5	48,244	17,716	201	0.23	752	200	0.92
Age of dam 6	73,427	25,278	202	0.19	763	202	0.91
Age of dam 7	47,227	16,144	202	0.24	741	200	0.93
Age of dam 8	24,560	8,733	200	0.33	695	196	0.96
Age of dam 9	11,854	3,973	196	0.49	587	190	1.04

Table 6. Least-squares means and standard errors for the interaction between sex of the calf and region of the United States for both the fixed and mixed models

		Fixed model			Mixed model		
Effect	Number observed	Effective number	LS mean (kg)	Std. error	Effective number	LS mean (kg)	Std. error
Bull calves							
Northeast	7,023	6,098	210	0.40	56	205	3.37
Cornbelt	11,765	10,239	211	0.31	141	207	2.12
South	13,304	11,175	205	0.29	127	204	2.23
Gulf Coast	6,405	4,992	192	0.44	45	194	3.77
Upper Plains	49,826	39,402	205	0.16	290	204	1.48
Lower Plains	42,886	32,986	204	0.17	297	200	1.46
Rocky Mts.	33,511	28,038	205	0.18	211	205	1.74
Desert S.W.	25,201	21,751	207	0.21	200	203	1.78
Pacific Coast	1,370	1,138	208	0.92	32	203	4.49
Heifer calves							
Northeast	7,627	6,656	186	0.38	56	184	3.37
Cornbelt	13,876	11,791	185	0.28	142	185	2.11
South	14,661	12,380	183	0.28	128	183	2.23
Gulf Coast	6,255	5,105	172	0.43	45	176	3.78
Upper Plains	47,210	37,592	186	0.16	290	186	1.48
Lower Plains	43,386	33,806	183	0.17	297	182	1.46
Rocky Mts.	30,965	26,116	185	0.19	211	188	1.74
Desert S.W.	25,371	22,137	188	0.21	200	185	1.78
Pacific Coast	1,433	1,159	189	0.91	32	185	4.48

Table 7. Least-squares means and standard errors for the interaction between sex of the calf and age of dam for both the fixed and mixed models

		Fixed model			Mixed model		
Effect	Number observed	Effective number	LS mean (kg)	Std. error	Effective number	LS mean (kg)	Std. error
Bull calves							
Age of dam 1	13,726	4,566	187	0.46	611	186	1.02
Age of dam 2	14,532	7,318	195	0.36	673	193	0.97
Age of dam 3	30,487	13,300	201	0.27	736	200	0.93
Age of dam 4	28,310	12,947	208	0.27	736	207	0.93
Age of dam 5	24,251	12,094	212	0.28	731	210	0.93
Age of dam 6	37,482	16,975	214	0.24	747	212	0.92
Age of dam 7	24,133	11,394	213	0.29	722	210	0.94
Age of dam 8	12,424	6,271	210	0.39	666	206	0.98
Age of dam 9	5,946	2,921	207	0.57	548	200	1.08
Heifer calves							
Age of dam 1	15,328	4,933	169	0.44	622	171	1.01
Age of dam 2	15,142	7,603	175	0.35	678	176	0.97
Age of dam 3	31,141	13,807	181	0.26	738	182	0.93
Age of dam 4	28,097	13,271	187	0.27	738	188	0.93
Age of dam 5	23,993	12,192	190	0.28	733	190	0.93
Age of dam 6	35,945	17,258	191	0.24	748	191	0.92
Age of dam 7	23,094	11,239	191	0.29	721	190	0.94
Age of dam 8	12,136	6,200	189	0.39	666	186	0.98
Age of dam 9	5,908	2,940	185	0.57	549	180	1.08

Table 8. Least-squares means and standard errors for the interaction between region of the United States and age of dam for both the fixed and mixed models

		Fixed model			Mixed model		
	Number observed	Effective number	LS mean (kg)	Std. error	Effective number	LS mean (kg)	Std. error
Northeast							
Age of dam 1	1,256	1,254	173	0.87	53	181	3.46
Age of dam 2	1,122	1,122	193	0.92	53	186	3.48
Age of dam 3	2,356	2,355	193	0.64	55	192	3.40
Age of dam 4	2,065	2,063	200	0.68	55	198	3.40
Age of dam 5	1,792	1,792	204	0.73	55	202	3.41
Age of dam 6	2,710	2,710	206	0.59	55	202	3.39
Age of dam 7	1,804	1,804	205	0.73	54	200	3.42
Age of dam 8	1,066	1,066	203	0.95	53	197	3.48
Age of dam 9	479	479	201	1.41	48	192	3.65
Cornbelt							
Age of dam 1	2,037	2,030	179	0.69	130	181	2.21
Age of dam 2	1,787	1,786	193	0.73	129	189	2.22
Age of dam 3	4.076	4,069	196	0.48	138	195	2.14
Age of dam 4	3,834	3,832	202	0.50	138	200	2.15
Age of dam 5	3,258	3,255	204	0.54	137	202	2.16
Age of dam 6	4,951	4,938	205	0.44	139	204	2.14
Age of dam 7	3,167	3,162	204	0.55	135	202	2.17
Age of dam 8	1,644	1,644	200	0.76	127	197	2.24
Age of dam 9	887	886	198	1.04	113	192	2.37
South							
Age of dam 1	967	964	176	0.99	103	178	2.49
Age of dam 2	3,117	3,114	183	0.55	121	182	2.29
Age of dam 3	4,466	4,465	191	0.46	124	191	2.26
Age of dam 4	3,902	3,900	197	0.49	124	197	2.27
Age of dam 5	3,407	3,406	199	0.53	123	200	2.27
Age of dam 6	5,371	5,366	201	0.42	125	202	2.25
Age of dam 7	3,517	3,517	201	0.52	123	201	2.28
Age of dam 8	1,978	1,978	200	0.69	117	198	2.33
Age of dam 9	1,240	1,240	198	0.88	109	192	2.41

Table 8. Continued

		Fixed model			Mixed model		
	Number observed	Effective number	LS mean (kg)	Std. error	Effective number	LS mean (kg)	Std. error
Gulf Coast							
Age of dam 1	424	424	164	1.50	39	170	4.05
Age of dam 2	1,123	1,123	169	0.92	43	174	3.87
Age of dam 3	1,954	1,954	177	0.70	44	183	3.81
Age of dam 4	1,952	1,952	184	0.70	44	189	3.81
Age of dam 5	1,696	1,696	190	0.75	44	193	3.82
Age of dam 6	2,647	2,656	191	0.60	44	194	3.80
Age of dam 7	1,636	1,636	192	0.76	43	194	3.83
Age of dam 8	813	813	189	1.08	42	189	3.91
Age of dam 9	405	405	185	1.53	38	180	4.08
Upper Plains							
Age of dam 1	9,161	9,156	180	0.32	278	181	1.51
Age of dam 2	6,427	6,426	189	0.39	275	188	1.52
Age of dam 3	15,894	15,893	191	0.25	286	192	1.49
Age of dam 4	14,484	14,481	198	0.26	286	198	1.49
Age of dam 5	12,411	12,409	202	0.28	284	202	1.50
Age of dam 6	18,682	18,661	203	0.23	286	203	1.49
Age of dam 7	11,708	11,695	203	0.29	282	202	1.50
Age of dam 8	5,769	5,763	199	0.41	272	197	1.53
Age of dam 9	2,500	2,499	194	0.62	246	192	1.61
Lower Plains							
Age of dam 1	3,797	3,793	182	0.50	264	177	1.55
Age of dam 2	8,019	8,016	181	0.35	283	181	1.50
Age of dam 3	13,616	13,612	190	0.27	292	189	1.48
Age of dam 4	13,102	13,102	196	0.27	291	195	1.48
Age of dam 5	11,271	11,271	200	0.29	290	198	1.48
Age of dam 6	17,353	17,351	201	0.23	293	199	1.47
Age of dam 7	11,238	11,236	200	0.29	289	198	1.48
Age of dam 8	5,652	5,651	197	0.41	277	193	1.51
Age of dam 9	2,224	2,224	195	0.66	245	188	1.61

Table 8. Continued

	Number observed	Fixed model: Effective number	Fixed model: LS mean (kg)	Fixed model: Std. error	Mixed model: Effective number	Mixed model: LS mean (kg)	Mixed model: Std. error
Rocky Mts.							
Age of dam 1	7,815	7,815	180	0.35	205	181	1.76
Age of dam 2	3,854	3,853	190	0.50	197	190	1.80
Age of dam 3	10,754	10,752	193	0.30	208	194	1.75
Age of dam 4	9,408	9,406	199	0.32	207	200	1.75
Age of dam 5	7,823	7,814	201	0.35	206	204	1.76
Age of dam 6	11,562	11,550	201	0.29	208	204	1.75
Age of dam 7	7,244	7,238	200	0.36	204	202	1.76
Age of dam 8	3,882	3,880	199	0.50	197	199	1.80
Age of dam 9	2,134	2,133	194	0.67	181	194	1.87
Desert S.W.							
Age of dam 1	3,476	3,473	184	0.52	184	179	1.86
Age of dam 2	3,990	3,989	187	0.49	187	185	1.84
Age of dam 3	8,107	8,107	194	0.34	196	192	1.80
Age of dam 4	7,245	7,245	201	0.36	195	199	1.80
Age of dam 5	6,163	6,163	204	0.39	194	201	1.81
Age of dam 6	9,575	9,573	205	0.32	196	202	1.80
Age of dam 7	6,554	6,554	203	0.38	193	200	1.81
Age of dam 8	3,560	3,560	199	0.52	185	196	1.85
Age of dam 9	1,902	1,902	196	0.71	170	191	1.93
Pacific Coast							
Age of dam 1	121	121	184	2.81	22	177	5.43
Age of dam 2	235	235	184	2.01	26	185	4.97
Age of dam 3	405	405	192	1.53	29	192	4.65
Age of dam 4	415	415	200	1.52	30	198	4.64
Age of dam 5	423	423	203	1.50	30	201	4.64
Age of dam 6	566	566	205	1.30	30	203	4.60
Age of dam 7	359	359	208	1.63	29	201	4.72
Age of dam 8	196	196	209	2.21	26	198	4.99
Age of dam 9	83	83	202	3.39	19	190	5.81

DISCUSSION

Results presented in the analysis of variance tables for the fixed and mixed models (Tables 2 and 3 respectively) indicated that all effects, except region of the United States in the mixed model, and all two-factor interactions were highly significant ($P < .005$) sources of variation in WW. As a statistical tool, however, the analysis of variance did not directly address the question of the proportion of the total variation being explained by each effect and interaction. To answer this question, the mean square for each effect in the analysis of variance was equated to its expected value, and the resulting equations were solved for their respective quadratic components. The quadratic component and the proportion of the total variation in WW being explained by each effect in the model is presented in Table 9. For the mixed model, the percent variation accounted for by each effect was expressed as a percent of the total variation among only the fixed effects in the model, however, the mean squares were adjusted for the random effects in the model by the solution process.

Main Effects

Sex of the calf

As much as 19.3 percent of the total variation in WW was explained by differences due to sex of the calf in the mixed model analysis. In the fixed model analysis, sex of the calf accounted

Table 9. Relative importance of each main effect and two-factor interactions in explaining the differences observed in WW

Effect	Fixed model: Quadratic component	Fixed model: Percent variation	Mixed model: Quadratic component	Mixed model: Percent variation[a]
Mean	57.3	4.4	90.4	9.5
Sex of calf (S)	222.5	17.2	182.8	19.3
Region of U.S. (R)	8.5	0.7	2.4	0.3
Age of dam (A)	51.8	4.0	36.4	3.8
S x R	0.9	0.0	0.5	0.0
S x A	0.7	0.0	0.6	0.0
R x A	1.8	0.1	0.3	0.0
Error	952.7[b]	73.5	634.8[b]	66.9

[a]Expressed as a percent of the variation among only the fixed effects.

[b]Variance component for random error.

for 17.2 percent of the observed variation in WW. The least-squares mean for bull calves was 205 kg in the fixed model analysis and 203 kg in the mixed model. Heifer calves, in both analyses, had a least-squares mean of 184 kg indicating that in the fixed model study heifer calves were 21 kg lighter and in the mixed analysis were 19 kg lighter than bull calves at weaning. Anderson and Willham (1978), in a similar mixed model study of weaning weight records from the Angus breed, found the bull calves to average 206 kg and the heifer calves to average 186 kg giving the bull calves a 20 kg advantage at weaning over the heifer calves. In their summary of results from 12 research studies, Petty and Cartwright (1966) reported that bull calves were, on the average, 17 kg heavier than heifer calves at weaning.

Region of the United States

Although region of the United States was a highly significant ($P < .005$) source of variation in WW from the fixed model study, it was clearly nonsignificant ($P > .20$) in the mixed model study. Results in Table 9 indicated that this effect accounted for less than 1.0 percent of the variation observed in WW from either model. The least-squares means for the nine regions in Table 5 indicated that the ranking of regions changed considerably depending on the model used (fixed versus mixed model). The Spearman rank correlation coefficient between the ranking of region means by the two models was 0.58.

The only clear result from the least-squares means was the slight penalty suffered by calves raised in the Gulf Coast region. In the fixed model analysis, calves raised in the Gulf Coast region averaged 182 kg which was 13 kg lighter in WW than the average of calves in the other eight regions. In the mixed model analysis, the difference between the Gulf Coast average of 185 kg and the average of the remaining eight regions was smaller at only 8 kg. These results indicated that the Gulf Coast region was an environment which, in general, was a harsher environment in which to raise Hereford calves to weaning. The reasons were no doubt quite complex but surely must have been related to the combination of high temperature and high humidity. These two factors might, at certain times of the year, have encouraged heavy parasitic infestations while during other times of the year promoted very low quality forage production in terms of protein and energy levels.

Results from the other eight regions of the United States indicated that the Hereford was equally well-suited to all parts of the country with only small differences (less than 4 kg for the fixed analysis and less than 5 kg for the mixed analysis) observed between region means. Even though the region definitions used by Anderson and Willham (1978) were not identical to the region boundaries used in the present study, they found that Angus calves raised in the southeastern United States averaged

191.5 kg while, overall, Angus calves in the remainder of the country averaged 197 kg at weaning.

In general, region differences in WW for Hereford calves were small after consideration was given, in the mixed model, to the variation accounted for by differences among herds within region, contemporary groups within herd, and cows within herd. Including these random effects in the mixed model resulted in adjustment of the least-squares region constants for the random effects within region, but in the fixed model analysis, the within region differences could only have been attributed to the overall region effect. This indicates that future studies of WW in Hereford calves do not need to include the effect of region of the United States in the model but rather do need to consider a proper accounting for the effects of differences among herds, contemporary groups within herd, and cows within herd.

Age of dam

The importance of age of dam in influencing WW is well-documented in the literature and has been summarized by Petty and Cartwright (1966) and by Anderson (1977). All reports unanimously agreed that WW increases with age of dam until the cow reaches maturity, that there is a plateau in WW level for one to several years, and then a decline in WW production that continues for the remainder of the life of the cow.

Results from this study have shown that age of dam was a highly significant ($P < .005$) factor influencing WW in Hereford calves. In the fixed model analysis, age of dam accounted for 4.0 percent of the total variation in WW while in the mixed model, it accounted for 3.8 percent. Least-squares means from both the fixed and mixed model analyses are shown in Figure 2 for each age of dam class. There was almost perfect agreement between the means from the fixed and mixed models for age of dam classes one through six. In classes seven through nine, however, means from the mixed model analysis were lower than the fixed model means. The lower mixed model means were largely the result of having included cows within herd as a random effect in the model thus eliminating the bias, first described by Lush and Schrode (1950), due to cow selection. Freeman (1973) has very well-summarized many of the biases and problems with age adjustment procedures.

In the present study, average WW among calves born to cows 20 to 27 months of age was 178 kg. Average WW increased for each age of dam class until the cows were five years old when the calves averaged 200 kg. There was a general plateau in WW production at 202 kg among mature cows from five to ten years old and a steady decline in production as cows progressed in age beyond ten years. These results agreed very closely with most of the results summarized by Petty and Cartwright (1966) and Anderson

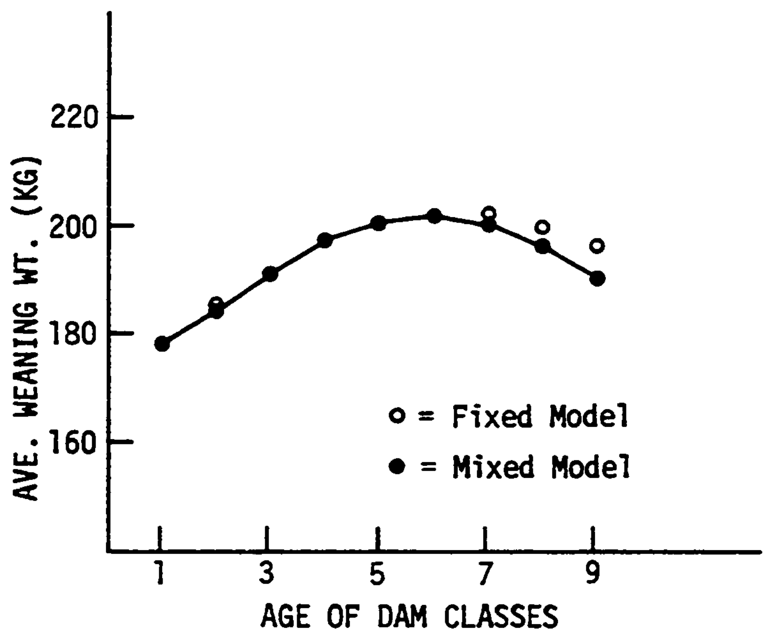

Figure 2. Least-squares means for each age of dam class from both the fixed and mixed models

(1977) and with the results reported by Anderson and Willham (1978) from the Angus breed.

Two-Factor Interactions

Sex by region

From the analyses of variance (Tables 2 and 3), the interaction between sex of the calf and region of the United States was a highly significant ($P < .005$) source of variation in WW. The difference between the bull and heifer least-squares means for WW in each region along with the percent of calves fed a supplemental creep ration prior to weaning are given in Table 10.

The difference between bull and heifer least-squares means was more variable across regions in the fixed model than in the mixed model. This indicated that the adjustment of WW records for the variation among herds and contemporary groups within herd had eliminated some of the variation which the fixed model had attributed to sex of calf. The differences in Table 10 also indicated that those regions of the United States (Northeast, Cornbelt, South), except the Gulf Coast, where the difference between bull and heifer means was larger than the overall difference due to sex were, in fact, those regions where supplemental feed was provided to 43 percent or more of all the calves in the region. Supplemental feed was provided to 34 percent or less of the calves in each of the five western regions. The larger difference in WW in favor of the bull

Table 10. Difference between bull and heifer least-squares means for WW within each region of the United States for both the fixed and mixed models

Region	Percent of calves creep-fed	Male minus female least-squares mean (kg)	
		Fixed model	Mixed model
Northeast	43	24	21
Cornbelt	51	25	22
South	60	23	21
Gulf Coast	51	20	19
Upper Plains	33	19	18
Lower Plains	34	21	18
Rocky Mountains	13	20	17
Desert Southwest	21	19	18
Pacific	25	19	18
Overall	32	21	19

calves in the Northeast, Cornbelt, and South suggests that the response to supplemental feed was greater in the bull calves than in heifer calves. To the extent that producers selectively fed bull calves supplementally while not feeding the heifer calves, the effect for contemporary groups within herd would have made proper adjustment for the confounding in the mixed model. Anderson and Willham (1978) reported similar results in the Angus breed.

Even though the interaction between sex of the calf and region of the United States was statistically a highly significant ($P < .005$) source of variation in WW, the amount of the total variation accounted for by the effect was less than 0.1 percent in either model. The evidence seems to be suggesting that the significance of this interaction was, at least in part, due to the differing levels of supplemental feeding practiced across the United States.

Sex by age of dam

A plot of WW least-squares means within each age of dam class for both the bull and heifer calves is given in Figure 3. Statistically, the interaction between sex of the calf and age of dam was a highly significant ($P < .005$) source of variation in WW. The significant interaction indicated that the amount by which average WW for bull calves exceeded the heifer average was not constant over all age of dam classes. The difference between the bull and

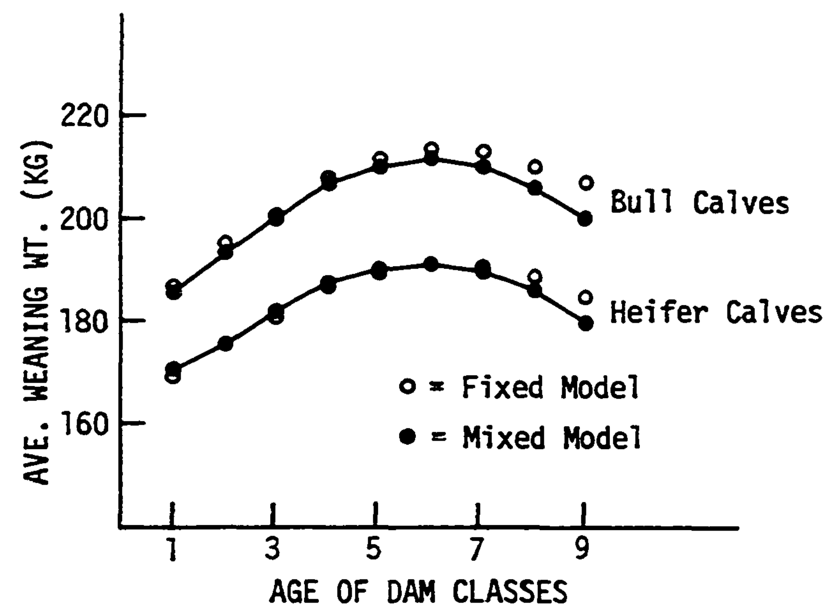

Figure 3. Sex of the calf least-squares means within each age of dam class for both the fixed and mixed models

heifer least-squares means within age of dam class is given in Table 11 for both models.

In the mixed model analysis, bull calves raised by cows 20 to 27 months of age when the calf was born exceeded their heifer contemporaries by 15 kg at weaning. This difference between the average WW of bulls and heifers increased as their respective dams increased in age to class five (five to six years) where the average difference was 20 kg. The 20 kg advantage for the bull calves then remained essentially constant as the age of dam increased beyond six years. Anderson and Willham (1978) also found the sex by age of dam interaction to be a significant source of variation for WW in the Angus breed. Thus, there appeared to be a depression, induced by the environment in which the calf was raised, in the growth rate of bull calves when they were raised by young cows which had not yet reached their mature level of milk production. This conclusion was also found by Schaeffer and Wilton (1974a) in their study of pre-weaning average daily gain for Angus and Hereford calves in Canada. Reports in the literature by Robison, et al. (1978), Rutledge, et al. (1971) and others on the relationship between milk yield and age of dam also supported the conclusion since calves raised by young cows were at a nutritional disadvantage due to the lower level of milk production from young cows. The effect of this milk deficiency, however, seemed to be more pronounced among the bull calves.

Table 11. Difference between bull and heifer least-squares means for WW in each age of dam class for both the fixed and mixed models

	Age of dam class								
Model	1	2	3	4	5	6	7	8	9
Fixed[a]	17	20	20	21	22	23	22	21	23
Mixed[a]	15	18	18	19	20	21	20	20	20

[a]All differences are in kilograms.

Region by age of dam

Plots of the age of dam least-squares means for each of the nine regions of the United States are presented in Figure 4. Statistically, the interaction effect between region and age of dam was a highly significant ($P < .005$) source of variation in WW for either model. Results in Table 9, however, indicated that this interaction accounted for less than 0.1 percent of the variation in WW.

The statistical significance of the region by age of dam interaction could have been the result of two general differences apparent among regions. First, there appeared to be a region difference in the increase in WW observed by the change in age of dam from age class one (20 through 27 months) to age class two (28 to 35 months). In the South, Gulf Coast, and Lower Plains, the increase in WW from class one to class two was only 4 kg in the mixed model analysis while in the Northeast, Cornbelt, Upper Plains, Rocky Mountains, Desert Southwest, and Pacific regions the increase was 5, 8, 7, 9, 6, and 8 kg respectively. The obvious management difference between these two groups of regions was the age of the cow when she delivered her first calf. In the South, Gulf Coast, and Lower Plains, there were more than twice as many calves born to cows in age class two than were born in age class one. In the other six regions, just the opposite was generally

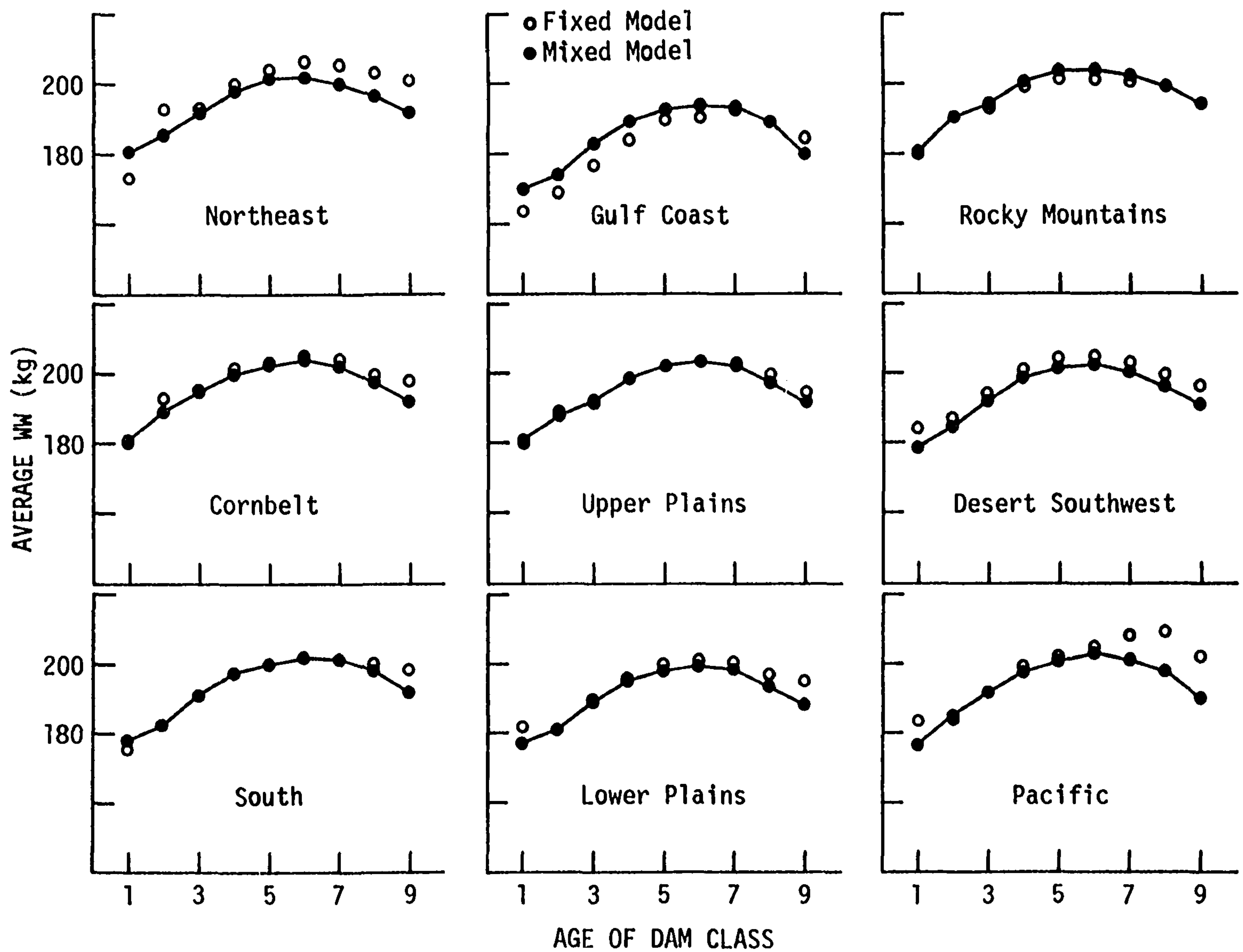

Figure 4. Age of dam least-squares means within each region for both the fixed and mixed models

found where more calves were raised by cows in age class one than by cows in age class two. Hereford breeders in the South, Gulf Coast, and Lower Plains apparently managed more of the young cows to calve for the first time at the older age, 28 through 35 months, while breeders elsewhere managed the young cows to calve first at 20 through 27 months of age. This management difference would result in the means for age class two in the South, Gulf Coast, and Lower Plains to be reflecting more closely the means observed for age class one in the remaining regions all of which were largely expressing the performance of calves raised by first calf heifers.

The second general difference apparent among regions, in the mixed model analysis, was the age at which cows reached their peak WW production. In the Rocky Mountain and Northeast regions, the peak level in WW was reached by cows in age class five (60 through 71 months), and this peak level of production was maintained through age class six (72 through 95 months). In the remaining regions of the United States, peak WW level was not reached until age class six.

Adjustment Factors

One of the objectives of most purebred Hereford breeders is to increase the average weaning weight of their herd. Increases in average weaning weight can be achieved by improving the nutritional environment of the herd, by implementing a sound breeding program designed to make the maximum genetic change in WW per year, and by combining both improved nutrition and management with the implementation of the breeding program. As levels of nutrition and management practices change with time, the ranking of individual animals on their own genetic merit for WW becomes more difficult due to the inability to separate genetic differences between animals from the nongenetic differences. One way to compensate for these nongenetic differences is to use statistical adjustments which standardize both the means and the variances among the diverse groups. Historically, these adjustments have corrected for differences in WW due to the sex of the calf and age of the dam before making within herd comparisons to select the replacement breeding animals for the next year. The Beef Improvement Federation (1975) recognized the possible existence of true breed differences for factors influencing WW, and they recommended that each breed association either develop new adjustment factors for the important effects influencing WW or verify, from their own data, that the adjustment factors then being used were, in fact, correct. This recommendation from the Beef Improvement Federation (1975) provided the motivation to complete the present study.

Results from this study have again validated the many studies already reported in the literature and summarized by Petty and Cartwright (1966), Anderson (1977), and the study of Angus records by Anderson and Willham (1978) which have clearly shown that both sex of the calf and age of dam are biologically and statistically highly significant ($P < .01$) factors influencing WW. In his summary of the literature, Anderson (1977) reported that, in results from three studies, the interaction between sex of the calf and age of dam was a significant source of variation in WW while in four other studies, the interaction was nonsignificant. Anderson and Willham (1978) reported the interaction to be a significant factor influencing WW in Angus calves, and they recommended that sex adjustment factors be developed within age of dam classes. Results from the present study have confirmed the statistical significance ($P < .005$) of the sex by age of dam interaction on WW, but, in the mixed model, the interaction accounted for less than 0.1 percent of the total variation accounted for by all the fixed effects in the model. Evidence from the present study indicated that the sex by age of dam interaction was not of major biological importance in WW for Hereford cattle. The study of preweaning average daily gain by Schaeffer and Wilton (1974a) also reported the interaction to be statistically significant in WW, but they concluded the effect was of only minor biological importance since it had accounted for less than 1.0 percent of the observed variation.

Anderson and Willham (1978) reported the region effect to be a small but significant ($P < .05$) factor in explaining variation observed in WW. They subsequently ignored the region effect and pooled estimates for the effects of sex and age of dam on WW across regions. There were no reports in the literature testing the importance of interaction between regions and sex or regions and age of dam. Results from the present study indicated that region differences, after properly accounting for within region effects due to herds, contemporary groups within herd, and cows within herd, were not significant ($P > .20$) in explaining variation observed in WW. The interactions between regions and both sex and age of dam, even though statistically significant ($P < .005$), accounted for less than 1.0 percent of the observed variation in WW. There appeared to be no overwhelming evidence to suggest that adjustment factors for sex and age of dam effects needed to be developed within regions of the United States. Adjustment factors were developed to correct WW records for differences due to sex of the calf and age of the dam. Adjustment of the WW record for the differences due to the age of the calf at weaning were accomplished by the standard correction to 205 days of age. Based on the results reported by Anderson and Willham (1978), management differences due to varying levels of supplemental feeding could best be adjusted from the data by making selections within herds and within contemporary groups so that all animals would have been treated equally.

The particular merits of additive and multiplicative adjustment methods have been discussed by Cundiff, et al. (1966b) and by Schaeffer and Wilton (1974b). Both methods of adjustment equalize the means among groups but the multiplicative adjustment also changes the variance by the square of the adjustment since var (cx) = c^2var (x) where c is a constant and x is a random variable. Reports in the literature by Koch, et al. (1959), Brinks, et al. (1961), Cundiff, et al. (1966b), and Anderson and Willham (1978) all have shown that an additive adjustment should be used to adjust WW records for the effect of age of dam and that a multiplicative adjustment is more appropriate for the elimination of differences in WW due to sex of the calf. The additive age of dam adjustment should be applied first and then the multiplicative adjustment for sex of the calf.

From the least-squares means in Table 5 for the mixed model analysis, the average WW for heifer calves was 10 percent below the mean for bull calves. This indicated that, to adjust heifer WW records to a bull calf basis, the heifer records must be multiplied by 1.10 and the bull calf records by 1.00. The study by Anderson and Willham (1978) recommended adjustments for sex differences of 1.10, 1.08, and 1.00 respectively for heifer, steer, and bull records indicating close agreement between the Angus study and the present study for the heifer record adjustment.

Additive correction factors to adjust WW records to a mature cow basis by eliminating the average effect of age of dam are given in Table 12. Calves raised by cows that were from 20 to 27 months

Table 12. Adjustment factors to eliminate differences due to age of dam by correcting WW records to a mature cow basis

Age of dam class	Class range (months)	Class mean (mixed model)	Adjustment factor
1	20 - 27	178	+ 24
2	28 - 35	184	+ 18
3	36 - 47	191	+ 11
4	48 - 59	197	+ 5
5	60 - 71	200	+ 2
6	72 - 95	202	0
7	96 - 119	200	+ 2
8	120 - 143	196	+ 6
9	144 - 240	190	+ 12

old when the calves were born were 24 kg lighter in WW than calves raised by mature cows. Calves raised by cows that were essentially eight months older (28 through 35 months) were 18 kg lighter than calves raised by mature cows, but they were six kg heavier at weaning than calves raised by the youngest cows. This six kg difference in WW between calves raised by cows in age classes one and two indicated that the definition of these age classes over a narrower range provided a more equitable adjustment of WW records from young cows as opposed to the age of dam grouping recommended by the Beef Improvement Federation (1976). Using their recommendation, cows from 21 through 33 months of age when the calf was born would have been in age class one, cows from 34 through 46 months in class three, and the age class two of the present study would have been eliminated. Schaeffer and Wilton (1974a) used even narrower six month intervals to define age classes among young cows. In practical application of the age of dam adjustments in Table 12, it appears that age of dam classes five, six, and seven could be combined to form the class for mature cows ranging from 60 through 119 months of age with only small losses in the adjusted WW.

Comparison Between the Fixed and Mixed Models

The two statistical estimation procedures used in the present study were developed using theory with vastly different assumptions as explained earlier. For different reasons, each of the two models was used in the present study. The fixed model was used primarily because it could produce estimates of the fixed effect least-squares constants with relatively easy computing techniques. In using the fixed model, it was known that no adjustments were being made to eliminate the bias due to cow selection discussed by Lush and Schrode (1950) and reviewed by Freeman (1973). It was also known that no consideration was being given to eliminate differences between contemporary groups within herd. In essence then, the fixed model, as applied in this study, ignored random effects known to be important sources of variation in WW, and the model produced least-squares constant estimates which were the difference between the overall averages for the particular classes. Thus, age of dam constant estimates were essentially the difference between the average of adjacent age classes making it possible for cows with only one record to contribute to the estimation procedure.

The mixed model, on the other hand, was used because by assuming some prior knowledge of the magnitude of the ratio of the error variance to the variances for herds, contemporary groups within herd, and cows within herd, estimates of the fixed effect constants could be obtained which were simultaneously adjusted for nearly all the effects known to be influencing WW. These adjustments for random effects in the mixed model produced least-squares estimates for the age of dam constants which were the average of differences in WW level only for cows which had more than one WW record. Consequently, any cows with only one record in the data would not have contributed to either the age of dam or sex estimates. The price that was paid for the additional adjustments of the fixed effect constants was greatly increased computing time and effort. In using the mixed model, it was known that estimates of variance components must be obtained from the same set of data that later was used to estimate the fixed effect constants because there were no previously published estimates in the literature. A measure of the agreement between the variance ratios used and the variance component estimates which could have been produced after solving the mixed model equations was not available since the computing effort required to obtain "first round" iteration estimates would have been at least as great as the computing effort required to obtain the fixed effect constants by absorbing the random effects. The outline for one way to proceed in iterating new estimates for the variance components was given by Schaeffer (1975).

Examination of results produced by the two estimation procedures indicated that age of dam means in older age classes were in fact lower from the mixed model than from the fixed model. If including cows within herd had eliminated the bias in age of dam constants due to cow selection, then the fixed model results would have been unfavorable to older cows because their WW records would not have received as much adjustment as the mixed model results indicate they deserved. Differences between the sex adjustments from the two models were small with the fixed model indicating an 11 percent adjustment and the mixed model indicating a 10 percent adjustment for heifer WW records. Had results from the fixed model been used to develop adjustment factors for WW, the same effects would have been chosen as significant effects which warranted adjustment.

The most obvious difference in results produced by the two procedures was in the size of the standard errors of least-squares means. The estimate of $\hat{\sigma}_e^2$ in the fixed model was 953 kg^2 while from the mixed model, the estimate of $\hat{\sigma}_e^2$ was 635 kg^2. Even though $\hat{\sigma}_e^2$ from the mixed model was 33 percent smaller than the fixed model estimate, without exception, the standard errors of mixed model least-squares means for fixed effect subclasses were larger than the corresponding means estimated by the fixed model. The reason for the larger standard errors for means estimated by the mixed model was apparent from the large reduction in the effective number of observations per subclass when compared to the fixed model effective numbers. As explained earlier, the effective number of observations per subclass was a reflection of the number of observations that would have occurred in each subclass if all cells in the design had been equally filled. Even though the mixed model had more accurately estimated least-squares constants for the fixed effects, the constants were subject to greater variation since adjustment for the large number of random equations had so dramatically reduced the effective number of observations per fixed subclass.

SUMMARY

Weaning weight records, provided by the American Hereford Association, from 382,075 calves born between 1958 and 1978 were used to study the effects of sex of calf, region of the United States, and age of dam and their interactions on 205 day adjusted weaning weight (WW). The importance of these effects was examined statistically by a fixed model which included only these effects and their interactions and by a mixed model which, in addition to the fixed effects, also included the effects for herds within region, contemporary groups within herd, and cows within herd. A comparison of the results produced by the two statistical models was made. Finally statistical adjustments were developed for correction of WW records to a bull calf raised by a mature cow.

Sex of the calf and age of dam were statistically highly significant ($P < .005$) factors influencing WW and accounted for 19.3 and 3.8 percent, respectively, of the variation observed in WW. Region of the United States, after accounting for differences among herds within regions, contemporary groups within herd, and cows within herd, was not a significant ($P > .20$) factor and explained less than 1.0 percent of the total variation in WW.

All the two-factor interactions were statistically highly significant ($P < .005$) sources of variation in WW, but none of the interactions accounted for more than 0.01 percent of the

observed variation. Because the amount of the total variation explained by each interaction was such a small proportion of the total variation, there was not a need to develop adjustment factors for age of dam within sex.

A multiplicative adjustment of 1.10 and 1.00 for heifer and bull calf records, respectively was recommended to eliminate differences in WW due to sex of calf. A set of additive adjustments was recommended to correct WW records for age of dam differences. These were +24, +18, +11, +5, +2, 0, +2, +6, and +12 kg, respectively, for cows in the age ranges 20 to 27, 28 to 35, 36 to 47, 48 to 59, 60 to 71, 72 to 95, 96 to 119, 120 to 143, and 144 and greater months of age.

BIBLIOGRAPHY

Aitken, A. C. 1934. On least-squares analysis of data with unequal subclass numbers. Proc. Royal Soc., Edinburgh 55: 42.

Anderson, J. H. 1977. Factors affecting weaning weights of beef cattle. Unpublished Ph.D. Thesis. Library, Iowa State University, Ames.

Anderson, J. H. and R. L. Willham. 1978. Weaning weight correction factors from Angus field data. J. Anim. Sci. 47: 124.

Beef Improvement Federation. 1975. Proceedings: Beef Improvement Federation Research Symposium and Annual Meeting, Des Moines, Iowa, May 19-21, 1975.

Beef Improvement Federation. 1976. Guidelines for uniform beef improvement programs. Beef Improvement Federation recommendation. U.S.D.A. Extension Service, Program Aid 1020.

Brinks, J. S., R. T. Clark, F. J. Rice, and N. M. Kieffer. 1961. Adjusting birth weight, weaning weight and preweaning gain for sex of calf in range Hereford cattle. J. Anim. Sci. 20: 363.

Brown, C. J. 1960. Influence of year and season of birth, sex, sire and age of dam on weights of beef calves at 60, 120, 180 and 240 days of age. J. Anim. Sci. 19: 1062.

Cardellino, R. and R. R. Frahm. 1971. Evaluation of two types of age of dam correction factors for weaning weights in beef cattle. J. Anim. Sci. 32: 1078.

Cundiff, L. V., R. L. Willham, and C. A. Pratt. 1966a. Effects of certain factors and their two-way interactions on weaning weight in beef cattle. J. Anim. Sci. 25: 972.

Cundiff, L. V., R. L. Willham, and C. A. Pratt. 1966b. Additive versus multiplicative correction factors for weaning weight in beef cattle. J. Anim. Sci. 25: 983.

Freeman, A. E. 1973. Age adjustment of production records: history and basic problems. J. Dairy Sci. 56: 941.

Harvey, W. R. 1960. Least-squares analysis of data with unequal subclass numbers. Reprinted in 1975 as U. S. Dept. Agr. Publ. ARS H-4.

Henderson, C. R. 1953. Estimation of variance and covariance components. Biometrics 9: 226.

Henderson, C. R. 1963. Selection index and expected genetic advance. National Academy of Sciences, National Research Council Publication 982: 141.

Henderson, C. R. 1973. Sire evaluation and genetic trends. Proceedings of the Animal Breeding and Genetics Symposium in honor of Dr. Jay L. Lush. Amer. Soc. of Anim. Sci., Amer. Dairy Sci. Assoc. and Poult. Sci. Assoc., Blacksburg, Virginia.

Koch, R. M., K. E. Gregory, J. E. Ingalls, and R. L. Arthaud. 1959. Evaluating the influence of sex on birth weight and preweaning gain in beef cattle. J. Anim. Sci. 18: 738.

Koger, M. and J. H. Knox. 1945. A method of estimating weaning weights of range calves at a constant age. J. Anim. Sci. 4: 285.

Lush, J. L. and R. R. Schrode. 1950. Changes in milk production with age and milking frequency. J. Dairy Sci. 33: 338.

Marlowe, T. J. and J. A. Gaines. 1958. The influence of age, sex, and season of birth of calf, and age of dam on preweaning growth rate and type score of beef calves. J. Anim. Sci. 17: 706.

Marlowe, T. J., C. C. Mast, and R. R. Schalles. 1965. Some non-genetic influences on calf performance. J. Anim. Sci. 24: 494.

Petty, R. R. and T. C. Cartwright. 1966. Genetic and environmental statistics for growth and conformation traits of young beef cattle. Texas Agr. Exp. Sta. Dept. Tech. Report No. 5.

Robison, O. W., M. K. M. Yusuff and E. U. Dillard. 1978. Milk production in Hereford cows I. Means and correlations. J. Anim. Sci. 47: 131.

Rutledge, J. J., O. W. Robison, W. T. Ahlschwede, and J. E. Legates. 1971. Milk yield and its influence on 205-day weight of beef calves. J. Anim. Sci. 33: 563.

Schaeffer, L. R. 1975. Disconnectedness and variance component estimation. Biometrics 31: 969.

Schaeffer, L. R. and J. W. Wilton. 1974a. Age of dam, sex and environmental interactions affecting preweaning average daily gains of beef cattle. Can. J. Anim. Sci. 54: 183.

Schaeffer, L. R. and J. W. Wilton. 1974b. Comparison of the effectiveness of multiplicative and additive adjustment factors in preweaning average daily gain of beef cattle. Can. J. Anim. Sci. 54: 519.

Searle, S. R. c1971. Linear Models. John Wiley and Sons, Inc., New York.

Sellers, H. I., R. L. Willham, and R. C. DeBaca. 1970. Effect of certain factors on weaning weight of beef calves. J. Anim. Sci. 31: 5.

Thompson, R. 1976. Relationship between the cumulative difference and best linear unbiased predictor methods of evaluating bulls. Anim. Prod. 23: 15.

United States Postal Service Zip Code Directory. 1977.

Yates, F. 1934. The analysis of multiple classifications with unequal numbers in the different classes. J. Am. Stat. Assoc. 29: 51.

ACKNOWLEDGMENTS

The advice, encouragement, and leadership of Dr. R. L. Willham, my major professor, in guiding me through the graduate program and the preparation of this manuscript is greatly appreciated.

Also appreciated are the many hours given unselfishly by Dr. P. J. Berger to stimulate and explore ideas in theory and applications of theory some of which provided the basis for this work. The support of Drs. A. E. Freeman, D. F. Cox, and M. J. Boehlje and their willingness to serve on the graduate committee is appreciated.

A very special thanks and considerable credit for the completion of this work is due my wife Debbie for without her support it is likely that this study would have never begun. Also thanks to our children, Amanda and Daniel, for their understanding.

It would be remiss not to thank Mrs. Maywood Burrows for it was she who planted my first seeds of interest in genetics and has encouraged, for many years, the development of those seeds.

Finally, the assistance and cooperation of the American Hereford Association in supplying the data for this study was most appreciated.